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Miscanthus production and processing in Ireland: An analysis of energy requirements and environmental impacts

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A B S T R A C T

The environmental impact of bioenergy supply systems can be determined using life cycle assessment methodologies. This study focuses on the impact of production of Miscanthus pellets and briquettes, potentially used to satisfy renewable energy requirements in Ireland. The impact categories considered are particularly important when assessing bioenergy systems; global warming potential, acidification potential, eutrophication potential, and energy demand. The scope of the study incorporates Miscanthus cultivation, harvest, processing and transport to a biomass distributor. The aim of the research is to evaluate the effects of changes in keys variables on the overall environmental impacts of the system. The scenarios examined include replacement of synthetic fertilisers with biosolids, Miscanthus processing by pelleting and briquetting, and transport distances of 50 and 100 km. Results indicate that maintenance and processing of the Miscanthus crop have the most environmental impacts with transport having less of an effect. Replacing synthetic fertiliser with biosolids results in a reduction in global warming potential of 23–33% and energy demand of 12–18%, but raises both acidification and eutrophication potential by 290–400% and 258–300%, respectively. Pelleting of Miscanthus requires more energy than briquetting, hence has higher impacts in each category assessed. Increasing the transport distance from 50 to 100 km, results in a small increase in each impact category. Miscanthus briquette production compares favourably with wood pellet, kerosene, and coal production, with Miscanthus pelleting proving more environmentally damaging.

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1. Introduction

In Ireland, there is an increasing awareness of the need to reduce greenhouse gas (GHG) emissions in line with Kyoto commitments and to develop alternative energy sources to reduce dependence on finite fossil fuel resources. The Irish government has adopted the European Union's (EU) renewable energy directive (RED) target of 20% of overall gross energy consumption by renewables by 2020, Irelands mandatory target being 16% [1], further driving the need to develop indigenous bioenergy resources.

Biomass is an important source of renewable energy. Biomass contributes about two-thirds of the renewable energy consumption in Europe, and almost 80% of the biomass consumption is wood and logging residues totalling 3.9% of overall energy consumption. The biomass pellet accounts for only 0.2% of gross final consumption [2]. This share is increasing as the pelleting of biomass has many benefits. The densification of biomass to pellet form improves its physical and chemical properties especially in terms of calorific value resulting in increased energy density, higher bulk density, and higher heating value [3]. The manufacture of wood pellets and briquettes are governed by a set of EN standards, ensuring that certain minimum fuel performance criteria are met [4–7].

The sources of raw material that can be used for successful pelleting depends on a number of factors; the moisture content of the feedstock, feedstock density, particle size, fibre strength, the feedstock's lubricating characteristics and the presence of natural binders such as lignin [8]. Focus has primarily been on the use of wood residues and sawdust for pellets, however, prices of these raw materials are increasing [2,9]. In addition, the increased demand for pellets for heating is causing shortages of the traditional raw materials, sawdust and wood shavings. As a result of these two factors, attention has turned to using alternative sources of biomass such as dedicated energy crops (Miscanthus, reed canary grass and hemp) and agricultural residues as raw material. Energy crops are seen as an attractive source of renewable energy as they offer reduced greenhouse gas emissions when compared to fossil fuels, coupled with potential carbon sequestration [10,11]. The economic viability of using more costly energy crops as raw materials has improved as the market prices for pellets increased about 45% from 1997 to 2006 [12].

Miscanthus is a perennial, woody, rhizomatous C4 grass species which originated in Southeast Asia and was imported into Europe as an ornamental grass. Miscanthus is commonly used as a raw material in building materials, geotextiles, and paper and packaging industries [13]. However, Miscanthus is also an ideal energy crop, yielding large quantities of high quality lignocellulosic biomass on a yearly basis over its lifetime, between 15 and 20 years [14,15]. The harvested biomass typically has a low moisture content, important for maximising energy output [16]. As such, Miscanthus has high net energy content when compared to other energy crops [17]. In addition, Miscanthus has high water and nutrient use efficiencies, making it a low input crop [18–20].

1.1. Environmental benefits of Miscanthus

The use of Miscanthus for energy production offers many environmental benefits including; climate, soil, biodiversity, and bioremediation.

1.1.1. Greenhouse gas reductions versus fossil fuels

Miscanthus combustion is considered to be carbon neutral as its combustion does not result in a net increase in atmospheric carbon dioxide (CO_2), due to absorption of CO_2 by the crop during photosynthesis [19]. The substitution of fossil fuels with Miscanthus in energy production results in significant avoided GHG emissions [19,21,22]. Hard coal combustion replaced with Miscanthus combustion for energy results in a reduction in GHG of 90% [14]. The use Miscanthus for energy production allows the displacement of primary energy sources such as coal and oil. Consequently, 1 t of Miscanthus can replace 0.6 t of hard coal [14], and 400 l of oil [23].

1.1.2. Soil

The deep rooting nature and rhizomatous structure of Miscanthus can result in a number of benefits to soil structure. The establishment of Miscanthus on tillage soils results in benefits in terms of improved nutrient and moisture retention, reduced wind and water erosion [24,25], and improved drainage [18]. These benefits are also observed, albeit to a lesser extent, when established on grassland sites once the crop reaches maturity [18]. Soil erosion is lower than on annual crops as cultivation and establishment is only repeated once over the lifetime of the crop [26,27]. Miscanthus cultivation increases the rate of nutrient cycling in the soil-plant system and enhances soil fertility [28].

During establishment of Miscanthus, high rates of mineralisation following ploughing can result in significant losses in organic carbon and nitrogen [18,29–31]. However, once established, the perennial nature of Miscanthus allows the accumulation of soil organic carbon (SOC) in differing quantities depending on soil type and previous land use [28,32,33]. Miscanthus cultivation on previously arable soils can result in SOC accumulation rates of over 1 t/ha [32,34]. Clifton-Brown et al. [35] estimated a gross SOC accumulation rate of 0.6 t C/ha/a over 15 years of Miscanthus cultivation on a previously grassland soil.

1.1.3. Bioremediation

The deep-rooting and perennial nature of Miscanthus provides a low soil-erosion environment making it ideal for the treatment and break-down of organic wastes. Energy crop plantations are considered particularly suitable for use as biological filters for treatment of wastewaters and sludges as their end use as fuels prevents direct entry of pollutants into the food chain [36,37].

1.1.4. Biodiversity

When replacing grassland with Miscanthus, an overall increase in biodiversity results in a greater number of species being present [18]. Similarly, biodiversity in Miscanthus is also higher than it is in conventional annual crops [22]. Miscanthus cultivation improves flora, fauna, mammal and soil biodiversity [24,38,39].

1.2. Why life cycle assessment

The use of Miscanthus for energy production offers many environmental benefits as discussed above, however it can lead to negative environmental consequences. Large-scale increases in biomass cultivation can pose risks to natural ecosystems by impacting on soil and water resources. As a result of these concerns, there have been many questions regarding the sustainability of bioenergy and the rate at which national governments, and the EU, are encouraging bioenergy development [40]. As such, the decision to use Miscanthus as a source of energy depends to a large degree on both its economic and environmental performance [21,22].

Life cycle assessment (LCA) is a tool which can be used to assess the environmental sustainability of energy production from a holistic perspective. Many studies have used life cycle assessment methodologies to estimate the potential environmental impacts of Miscanthus production [21,22,41–44]. Few of the reviewed studies focus on the results to changes in management and production practices. The majority of the literature pertaining to LCA studies of pellets focuses on the production of wood pellets. Both the emissions and the energy requirements of wood pellet production have been analysed in previous studies [45–50] with few relating to pellets from alternative sources, poplar [51], straw [3] and Miscanthus [52].

2. Materials and methods

2.1. Goal and scope

The aim of this paper is to analyse Miscanthus production and processing in Ireland, with regard to emissions and energy requirements throughout the life cycle. In order to fill the gaps identified in the literature, in particular pertaining to effects of management scenarios and pelleting of Miscanthus, this paper assesses the effect of changes in key variables on the overall environmental performance of the system. It is envisaged that the results will provide insights into the optimal performance of the Miscanthus production and processing chain in terms of the environmental impacts studied. Specific attention is paid to the production of Miscanthus using two different fertilisers, synthetic and biosolid. Two processing methods are assessed; briquetting and pelleting. And two transport distances, 50 and 100 km (km), are evaluated. As this study focuses of the production, processing and transport of the processed biomass to a distributor it is thus defined as a 'cradle-to-gate' LCA study.

2.1.1. Functional unit

As the focus of this paper is on the production of Miscanthus products for the generation of heat or electricity, it is useful to express the results in terms of energy content of the final delivered product. Therefore, the reference functional unit is 1 GJ of energy embodied in the processed Miscanthus at the gate of the processor. Energy content is commonly used as a functional unit in Miscanthus production studies [22,43,44]. Using a measure of the performance of the system in terms of energy output allows the system to be compared to other energy production systems [53,54].

2.1.2. System description

The boundaries of the system are illustrated in Fig. 1. The system encompasses all aspects of the pelleting system; raw material acquisition (crop cultivation and harvesting), feedstock processing (pelleting and briquetting), and transport to the distributor.

The entire burden of the system is allocated to pellet/briquette production. No loads allocation is required in the feedstock option as the entire harvestable yield is considered as fuel.

Description of Miscanthus processing cycle outlined in Fig. 1:

The ground is prepared prior to seeding. This involves application of herbicide to control actively growing weeds, ploughing, and finally disking to prepare a stale seedbed for planting. The Miscanthus crop is planted with a modified potato planter to a density of 15,500 cuttings per hectare. The site is consolidated by rolling and a residual herbicide applied. Fertiliser is not applied during the first two growing seasons. Beyond this, fertiliser is applied 14 times over the life of the Miscanthus plantation (after every harvest). Herbicide is also applied at this stage. The application of synthetic fertilisers and biological fertilisers are compared in this study. After an establishment period of 2 years, Miscanthus is harvested on a yearly basis. The crop is mown and left in the field to dry before baling. The bales are subsequently transported 5 km to the farm yard. It is chopped and further dried using a modified grain dryer. The Miscanthus is then pelleted or briquetted. The processed Miscanthus is transferred to trucks and is transported to the distributor. In this analysis two transport distances are compared; 50 and 100 km. The Miscanthus crop is removed from the site at the end of the crops life (approximately 17 years) by the application of herbicide such as glyphosate followed by ploughing. This leaves the majority of the root system in place without damaging the soil structure [15].

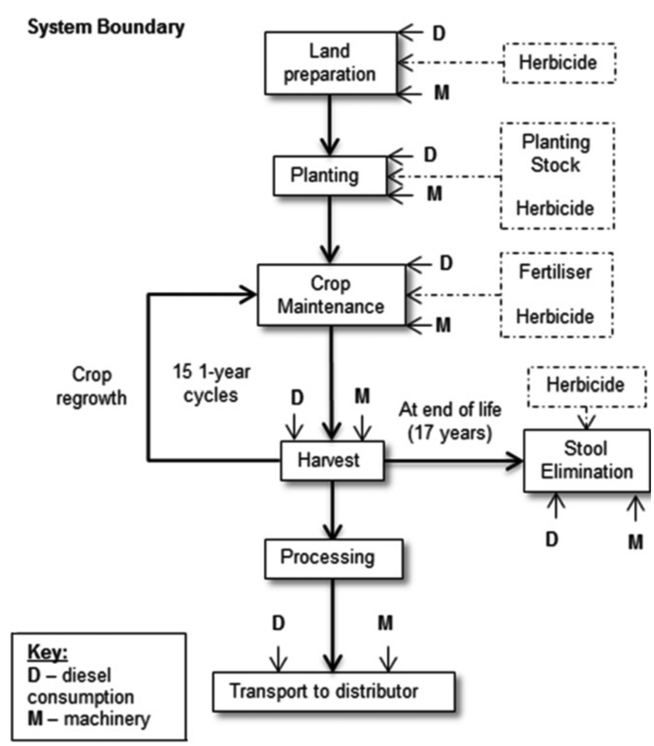


Fig. 1. System diagram.

2.2. Inventory analysis

The LCA was conducted in Simapro 7.3 [56] using primary and secondary data from various sources, the sources of data and use of the data are outlined in the following sections.

Data specifically relating to Miscanthus production in Irish conditions is used wherever possible. Where there are limitations in this data, other standard data for Miscanthus and general agricultural production reported in the literature is used. The Miscanthus production cycle in this model is based on data from Teagasc Miscanthus Best Practice Guidelines [15] and other literature [16,35,57,58]. The data for pelleting was obtained from trials in the University College Dublin research laboratory. This data was combined with pelleting infrastructure data from the ecoinvent database [59]. The gathered data was supplemented with data from ecoinvent databases.

Table 1 outlines frequency of field operations over the lifetime of the crop.

Table 2 details the inputs to the cropping system over the lifetime of the Miscanthus plantation (17 years).

2.2.1. Field inputs

Nursery stock production was modelled based on data from Jungbluth et al. [57]. Nitrogen, phosphorus and potassium fertiliser data was obtained from the Danish LCA Food Database [60]. Biosolid data was obtained from [36,61,62]. Pesticide production is based on data from Nemecek et al. [63].

2.2.2. Machinery and fuel consumption

Data regarding the manufacture and fuel consumption of conventional agricultural machinery used in Miscanthus cultivation were obtained from a report by Nemecek et al. [63]. For machinery specifically related to Miscanthus harvesting, such as the baler, not contained in the ecoinvent databases, other sources of data were used [22]. Data on tractor and trailer manufacture was obtained from the ecoinvent database [64].

2.2.3. Field emissions

The cultivation of Miscanthus and the use of fertilisers result in emissions to air, soil and water. The ammonium contained in fertilisers can be released to the atmosphere as ammonia (NH_3) through the process of volatilisation. Rates of volatilisation depend on a number of factors; fertiliser type, soil type and pH, and weather conditions [65]. In this study, NH_3 volatilisation is assumed to be 2% of applied nitrogen according to sources [63,66]. For the application of biosolids, it is assumed that 26% of the N contained in the biosolids is released as ammonia according to Nemecek et al. [63].

Nitrous oxide (N_2O) is produced naturally as a product in the denitrification and nitrification processes by soil micro-organisms. The addition of nitrogen to the cropping system in the form of both synthetic and biological fertilisers enhances N_2O formation. N_2O is a powerful greenhouse gas and is has 298 times the global warming potential of 1 kg of CO_2 equivalent [67]. In this study N_2O formation is estimated to be 1.25% of available nitrogen from synthetic sources after ammonia volatilisation. This estimation is consistent with those used in published literature [65,68,69]. As emissions factors for both synthetic fertiliser and biosolids are similar, N_2O emission rates for both are assumed to be the same according to the Biosolids Emissions Assessment Model (BEAM) [70].

Preliminary results show low levels of nitrate leaching compared with other crops [19]. Higher leaching rates in the year after establishment are observed, however in subsequent years nitrate leaching reduces to rates comparable to those from unfertilised grass [71]. The nitrate leaching rate is estimated according to IPPC data [68], it is assumed that 30% of applied nitrogen in both synthetic and biosolid fertilisers is lost in leaching to groundwater while 0.75% is converted to N_2O.

During the nitrification process in soils, nitrogen oxides (NO_x) may be produced in parallel with N_2O. NO_x emissions in this study for both synthetic and biosolid fertilisers are estimated according to Nemecek et al. [63].

Table 1
Summary of field operations.

Field operation	Frequency of operation (per 17 year cycle)
Pre-ploughing herbicide	1
Plough	2
Disk	1
Plant	1
Roll	1
Harvest	14
Herbicide	15
Fertilise	14

Table 2
Data summary of inputs to cropping system.

Plan	Input	Frequency (per 17 year cycle)	Application rate (kg/ha)	Total (kg/ha) over life cycle
Land preparation	Water	1	200	200
	Glycophosphate	1	1.8	1.8
Crop Establishment	Cuttings	1	15,500u	15,500u
	Water	1	500	500
	Glycophosphate	1	1.44	1.44
	Pendimethalin	1	1.09	1.09
Maintenance	Water	14	200	2,800
	Nitrogen	14	60	840
	Phosphorous	14	9	126
	Potassium	14	58.75	822.5
	Pendimethalin	14	1.37	19.17
Crop removal	Glycophosphate	1	1.8	1.8

2.2.4. Harvest and yield

Yields of Miscanthus are lower in Northern Europe (11–16 t/ha) in comparison to Southern Europe (24 t/ha) as it is limited by temperature [72]. Peak yield occurs in autumn; however it is common practice to postpone harvest until the following spring. This improves the quality of the biomass as nutrient and moisture contents are reduced, and energy content is increased. The yield loss is compensated by the increase in energy content [23]. The average harvestable yield from 1 ha of Miscanthus in Ireland is assumed to be 11.5 dry t/ha from a 1 year harvest cycle [15]. Harvest losses represent an important loss during the conversion of the standing yield of the crop to the harvested yield. Harvest efficiency was assumed to be 90% according to Styles and Jones [58].

Basic elements of current harvesting technology can be used [23]. Miscanthus mowing is based on data from Nemecek et al. [63]. Miscanthus baling is based on data from Smeets et al. [22] and Nemecek et al. [63].

2.2.5. Drying

The harvested Miscanthus must be dried to a moisture content in order to be stored in a stable manner and to allow processing to pellets and briquettes [23]. The required moisture content for pelleting and briquetting is 10%. Upon mowing, the Miscanthus is

left in windrows in the field to further reduce the moisture content. It is then baled, and transported 5 km to the processing facility where it is chopped. Approximately 50% of the Miscanthus received at the processing facility is at a suitable moisture content for processing, while 50% is further dried using a modified grain dryer [73]. Data for the grain dryer is obtained from Nemecek et al. [63].

2.2.6. *Crop processing*

The Miscanthus bales are chopped when received at the processing facility. Data on the chopper is obtained from Werner et al. [74]. The crop is further processed based on whether pellets or briquettes are produced.

Energy requirements for the pelleting process Table 3 were obtained from trials in the University College Dublin research laboratory at Lyons Estate pellet plant in Ireland. The pellet machine used is a 250 kg/h micro pellet pressing line by Green-Forze. The total installed power requirement for the system is 57 kW. Further data on the pellet plant infrastructure was obtained from Werner et al. [74].

Productivity and energy requirements of the briquetting process were obtained from Hughes [73]. The data is outlined in Table 4.

2.2.7. *Transport*

It is assumed that the biomass is transported an average distance of 50 km from the processing plant to the distributor in a 44 t (design gross vehicle weight) truck. The return trip is assumed to be empty. Data for transport is obtained from Spielmann et al. [64].

Table 3
Data summary of pelleting process.

Power requirement (kw h)	38.55
Output (kg/h)	150
Net calorific value (MJ/kg)	18

Table 4
Data summary of briquetting process.

Power requirement (kw h)	50
Output (kg/h)	400
Net calorific value (MJ/kg)	18

2.3. *Life cycle impact assessment*

The attributional LCA for Miscanthus cultivation and processing in this case was carried out using CML 2001 [75] and ecoinvent methods [76]. The impacts assessed include acidification potential (AP), eutrophication potential (EP), and global warming potential (GWP). The cumulative energy demand (CED) is also evaluated, allowing the energy ratio (energy out versus energy in) of the system to be calculated.

2.3.1. *Global warming potential*

Global warming potential (GWP) is an important environmental impact to consider in the evaluation of renewable energy systems. GWP refers to the potential of the system to trap greenhouse gases in the atmosphere, leading to climate change. Gases which contribute to global warming include carbon dioxide, methane and nitrogen dioxide. GWP is expressed in kg CO_2-equivalents [75].

2.3.2. *Acidification potential*

Acidification potential (AP) is an important environmental impact to consider when evaluating bioenergy systems as it is expected to increase with increased production of biomass. AP is caused by the emission of acids or acid forming substance the environment, resulting in acidification of soil and water. Acidification harms natural life such as fish and trees, and also causes damage to buildings etc. The main sources for emissions of acidifying substances are agriculture and fossil fuel combustion. Examples of contributing substances include; sulphur dioxide, nitrogen oxides and ammonia. AP is expressed in kg SO_2-equivalents [75].

2.3.3. *Eutrophication potential*

Eutrophication potential (EP) is another environmental impact important in the evaluation of bioenergy systems. EP is defined as the potential of nutrients to cause over-fertilisation of water and soil which in turn can result in increased growth of undesirable biomass. This biomass has negative impacts on other life in the ecosystem. Contributing substances include; phosphates, nitrates, ammonia, nitrous oxides etc. EP is expressed in kg PO_4-equivalents [75].

2.3.4. *Energy demand and energy ratio*

Cumulative energy demand (CED) of a product or system characterises both the direct and indirect energy use throughout the life cycle. It is a particularly important evaluation of bioenergy

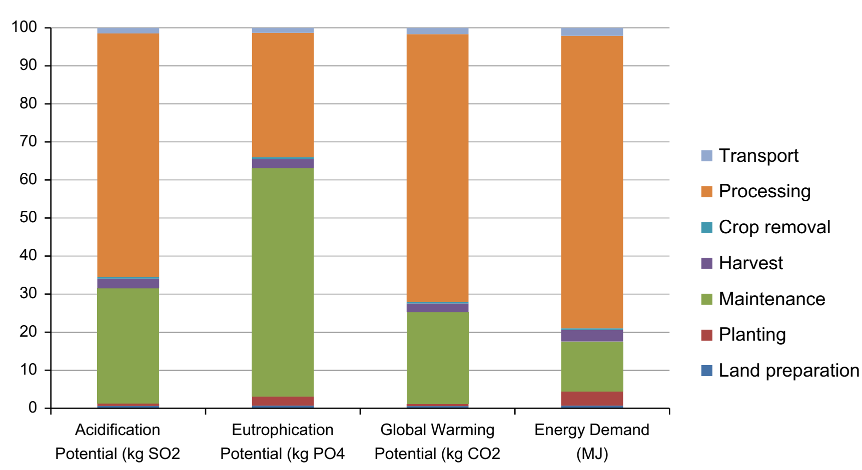


Fig. 2. Process contribution to AP, EP, GWP and CED.

systems in order to ensure that more energy is not consumed than produced. CED is expressed in mega joules (MJ).

In addition, Huijbregts et al. [77] found that CED correlates well with most environmental life cycle impact categories and can be considered an appropriate proxy indicator for environmental performance.

A further way to assess advantages of renewable energy systems may be to evaluate the pure energy ratio of the system. The term "energy ratio" is used to characterize relations between the energy input and output. Energy ratio is a ratio between the energy output and energy input according to the following equation;

ER = Eo/Ei
where
Eo—energy output,
Ei—energy input,
ER—energy ratio [78].

3. Results

Table 5 gives the results of the impact assessment for the base case scenario; production of Miscanthus pellets using synthetic fertiliser and transporting the product 50 km to the distributor. The table gives the impacts per gigajoule (GJ) of energy contained in the pellets over each stage of the life cycle. The production of 1 GJ of Miscanthus pellets requires 272.1 MJ of energy and results in the emission of 20.23 kg CO_2-eq. In addition to this, 0.1118 kg SO_2-eq and 0.0329 kg PO_4-eq are released.

Figure 2 highlights the percentage contribution of each stage in the life cycle to the overall environmental impacts. An analysis of the results depicted in Fig. 2 shows that the largest contributor to AP, GWP, and CED is the pelleting process. This step utilises a large quantity of delivered energy in the form of electricity. Maintenance causes the most eutrophying emissions. The production of this electricity results in the largest degree of emissions in the life cycle. When considering the life cycle of the energy crops in isolation, it is clear that the maintenance step results in the most emissions. This is due to the production and application of synthetic fertilisers.

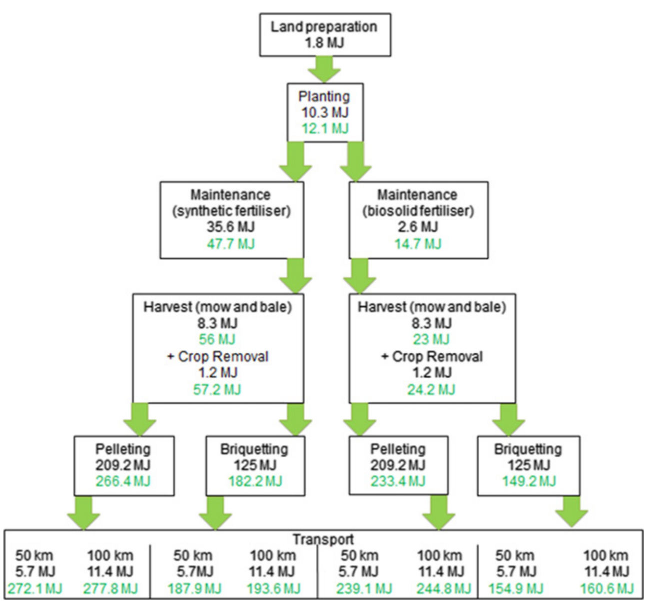


Fig. 3. Energy requirements of life cycle stages (MJ per GJ of energy produced).

Figure 3 gives the energy demand required to produce 1 GJ of processed Miscanthus for each stage in the life cycle, including the alternative management options. The black figures indicate the energy demand for each step while the green figures indicate the cumulative energy demand throughout the chain.

The energy ratio of the system can be calculated by comparing cumulative energy demand in Table 5 to the energy content of the Miscanthus pellets and briquettes outlined in Tables 3 and 4. Table 6 outlines the energy ratios of the different management scenarios. Results show that the best scenario in terms of energy performance is the production of Miscanthus briquettes using biological fertilisers and transporting the product 50 km. The worst performing scenario involves the use of synthetic fertilisers in producing Miscanthus pellets which are then transported 100 km.

3.1. Alternative fertilisers

As shown by the results, the production of synthetic fertilisers makes a large contribution to each of the impact categories studied due to the energy and resources used to produce them. The application of biosolids to the crop as an alternative fertiliser has the potential to reduce these impacts through the utilisation of a waste product to meet the crops nutrient requirements. Sensitivity analysis was carried out on substituting biosolids for synthetic fertilisers. Table 7 shows that using biosolids in place of synthetic fertiliser increases both acidification and eutrophication potential by 290–400% and 258–300%, respectively. However, global warming potential and cumulative energy demand are reduced by 23–33% and 12–18%, respectively.

3.2. Processing

The pelleting of Miscanthus utilises a large quantity of delivered energy (257 kW h/t) in the form of electricity. This energy use

Table 6
Energy ratios of the different management scenarios.

Scenario	Energy ratio
Synthetic fertiliser, *pellets*, 50 (Km)	3.7
Synthetic fertiliser, *pellets*, 100 (Km)	3.6
Synthetic fertiliser, *briquettes*, 50 (Km)	5.3
Synthetic fertiliser, *briquettes*, 100 (Km)	5.2
Biological fertiliser, *pellets*, 50 (Km)	4.2
Biological fertiliser, *pellets*, 100 (Km)	4.1
Biological fertiliser, *briquettes*, 50 (Km)	6.5
Biological fertiliser, *briquettes*, 100 (Km)	6.2

Table 5
Results of the impact assessment of the Miscanthus pellet chain per GJ of energy contained in the pellets.

Impact category	Unit	Land prep	Planting	Maintenance	Harvest	Crop removal	Pelleting	Transport	Total
AP	kg SO_2 eq	0.0007	0.0007	0.0339	0.0028	0.0004	0.0717	0.0016	0.1118
EP	kg PO_4-eq	0.0002	0.0008	0.0197	0.0008	0.0002	0.0107	0.0004	0.0329
GWP	kg CO_2 eq	0.11	0.11	4.88	0.47	0.07	14.25	0.34	20.23
CED	MJ	1.8	10.3	35.6	8.3	1.2	209.2	5.7	272.1

Table 7
Overall results—management scenarios (per GJ of energy contained in processed biomass).

11976 (km)	AP (kg SO_2 eq)	EP (kg PO_4 eq)	GWP (kg CO_2 eq)	CED (MJ)
Synthetic fertiliser, *pellets*, 50 (km)	0.1118	0.0329	20.23	272.1
Synthetic fertiliser, *pellets*, 100 (km)	0.1135	0.0333	20.56	277.8
Synthetic fertiliser, *briquettes*, 50 (km)	0.0822	0.0285	14.82	187.9
Synthetic fertiliser, *briquettes*, 100 (km)	0.0838	0.0289	14.49	193.6
Biological fertiliser, *pellets*, 50 (km)	0.4411	0.1186	15.50	239.1
Biological fertiliser, *pellets*, 100 (km)	0.4427	0.1191	15.84	244.8
Biological fertiliser, *briquettes*, 50 (km)	0.4114	0.1143	9.76	154.9
Biological fertiliser, *briquettes*, 100 (km)	0.4131	0.1147	10.10	160.6

has a major effect on each impact category assessed, as can be seen in Fig. 2. Briquetting of Miscanthus requires 125 kW h/t, approximately half the requirement of pelleting. As such briquetting affecting the contributions to all four categories assessed; reducing AP by 7–26%, EP by 4–13%, GWP by 28–37%, and CED by 30–35%.

3.3. Transport distance

Two transport scenarios were analyse; transport of the pellets and briquettes over two distances, 50 and 100 km. The results show that the transport distance has a smaller effect on the impact categories, with increasing the transport distance to 100 km increasing AP by 0.4–2%, EP by 0.4–1.5%, GWP by 2–3.5%, and CED by 2–4%.

3.4. Greenhouse gas comparison with other fuels

One of the main benefits of bioenergy utilisation is the reduction in GHG emissions achieved when compared to fossil fuel systems [19,21,22]. Miscanthus pellets and briquettes can be compared to two other biomass fuels; wood pellets and firewood. Sjølie and Solberg [9] estimated emissions from wood pellet production to be in the range of 8–37 kg CO_2eq/GJ, depending on raw material, source of electricity used and transport methods. Hagberg et al. [48] estimated emissions from pellet production in Sweden to be 3–4 kg CO_2eq/GJ if waste heat is utilised in production, rising to 19 kg CO_2eq/GJ if oil is used, both comparing favourably to Miscanthus pellet production which emits 15.5 to 20.23 kg CO_2eq/GJ. Wood pellets may have lower emissions than Miscanthus products as they are produced from wood processing by-products and the share of emissions is allocated between the products [48].

Miscanthus pellets replace kerosene and Miscanthus briquettes replace coal as fuel in home heating systems. Data on the environmental impacts of coal and kerosene supply were obtained from the ecoinvent database [79,80]. Greenhouse gas emissions associated with Miscanthus briquette production are comparable to coal and kerosene production which emit approximately 12.28 kg CO_2 and 11.69 kg CO_2 per GJ, respectively. These figures do not include transport to Ireland which would increase emissions if included. Although outside the scope of this analysis, further GHG reductions are likely to occur when comparing biomass combustion to fossil fuel combustion. The biomass is assumed to emit only the carbon it had accumulated from the atmosphere during its growing cycle, therefore biomass combustion is often assumed to be carbon neutral.

4. Conclusion

The aim of this study was to analysis the production and processing of Miscanthus from a life cycle perspective, identify hotspots in the production chain and identify the effectiveness of management practices which affect these hotspots. The results of this study clearly identify maintenance and processing of the Miscanthus crop as the stages of the life cycle which contribute most to each of the impact categories; acidification potential, eutrophication potential, global warming potential, and energy demand. This finding echoes those outlined in Styles and Jones [52], where cultivation and pelleting of Miscanthus contributed most to life cycle GHG emissions. The pelleting of the harvested Miscanthus utilises a large quantity of energy in the form of electricity. The production of this electricity results in the largest degree of emissions in the life cycle. The energy requirement during pelleting is also higher compared to other studies [22] which results in higher life cycle emissions. This may be due to the fact that the data is based on lab scale results; energy requirements may be lower on an industrial scale. When this step is replaced by briquetting, which has a lower energy demand than pelleting, significant savings are made to each of the impact categories.

The other main contributor to each of the impact categories is the maintenance of the Miscanthus crop. This is due to the production and application of synthetic fertilisers. The production of synthetic fertilisers is an energy intensive process and utilises non-renewable fossil fuels. Emissions from maintenance are higher than other studies which assume that no fertiliser inputs are required [21,41]. Experience in Ireland suggests that inputs are required to achieve a reasonable yield (circa 11 t/ha) according to Byrne [81]. By utilising biosolid fertilisers, savings can be made in terms of energy use and greenhouse gas emissions. However, the application of biosolids increases the acidification and eutrophication potential. As such, the decision to apply biosolids or synthetic fertiliser would require a careful analysis of both positive and negative effects.

Varying the transport distance has a smaller effect on the results, however, the benefits of keeping the transport distance as low as possible are identified.

The data for the power requirement for the pellet production process is based on results from lab-scale testing. As such, additional analysis will require data from commercial scale pellet manufacture. However, in Ireland Miscanthus briquettes are manufactured on a small scale, while Miscanthus pellets are not currently manufactured on a commercial scale at all.

The results of the study identify hotspots in the Miscanthus processing chain which may enable the development of optimal management scenarios to assist in the further progress in a developing biomass industry in Ireland.

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